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FIBRESHIP project: Engineering, production and life cycle management for the complete construction of large length fibre-based ships.

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Abstract

Fibre-Reinforced Polymer (FRP) materials are widely used in the construction of small-length vessels due to their light weight and high strength to weight ratio. However, the use of FRP materials in vessels above 50 m length is only allowed to secondary structural elements of the vessel. Hence, it is necessary to promote the creation of new regulatory frameworks to permit the construction of large-length vessels using composite laminates in all parts of the vessel structure to enable the development of this interesting technology for the reduction of weight. FIBRESHIP proposes to create a new market focused on the construction of large-length vessels based uniquely on lightweight composites. The results of this project are attracting considerable interest within the shipping industry as the extensive use of FRP materials in large-length vessels induces an important reduction of the weight with respect to the conventional steel ships. This significant weight reduction decreases the vessel bunkering consumption, increases the payload cargo capacity, and avoids the corrosion phenomena in the vessel among other identified benefits.

Keywords: Composites; FEM; Structural Health Monitoring; Guidelines, Fire resistance; Regulation; Lightweight vessels.

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1. Introduction

Europe is today a major player in the global shipbuilding and shipping industry. As a result, the European shipping industry is responsible for the construction of 40% of world's fleet. In particular, the European shipbuilding companies remain in a leading position in the international market thanks to a clear determination to offer high added-value vessels using the most advance state-of-the-art technology.

Recently, the use of fibre-Reinforced Polymers (FRP) materials in vessels are extensively used for building lightweight hull structures of vessels with a length up to about 50 meters. However, the use of those materials for longer vessels is limited to bulkheads and other secondary structural components of the ship. This limitation is attributed to the fact that the use of FRP in large-length composite ships may adversely affect the safety level of the vessel, as reflected by the Convention for the Safety of Life at Sea (SOLAS). Therefore, different technology gaps as fire resistance (steel is a non-combustible material and stays stronger for longer in a fire than FRP) should be considered to demonstrate the feasibility of using FRP materials in large-length ships from technical and economic point of view. In order to fill these gaps, the FIBRESHIP project proposes a selection methodology of innovative composite materials for marine applications, innovative guidelines for the design of composite vessels, specific bonding solutions between the different structural elements of the vessel, new production procedures for large-length composite vessels, a set of computational tools for design assessment, analysis of vessel structural health monitoring strategies, experimental tests for validation of numerical models, and the manufacturing of a demonstrator to validate the results of both experiments and numerical simulations. In addition, a market analysis considering all the research and findings is also carried out in order to introduce these new technologies to the shipping and shipbuilding sector.

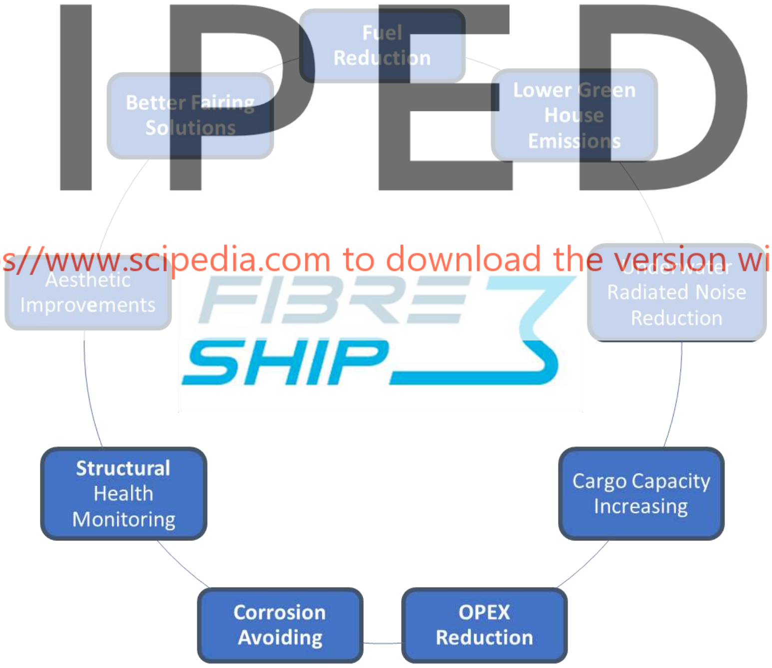

Fig. 1 Summary of the main expected benefits of FIBRESHIP

FIBRESHIP project is an European R&D project (Grant Number 723360) funded by the European Commission in the framework of H2020 program. It is made up of 18 partners of 11 countries of Europe, representing all the stakeholders of the maritime sector. The FIBRESHIP project started on June 2017 and is expected to conclude by the end of May 2020. Therefore, this innovation project focused on the design, construction and life-cycle assessment of large-length lightweight vessels along the three years of project duration.

The main benefits of the massive application of fibre-based materials in the construction of vessels are well-known. Firstly, a significant weight reduction of the vessel as compared to steel-based ships, which implies a substantial bunkering saving, reduction of powering needs and/or a potential increase in payload cargo capacity. Secondly, the extensive use of composite materials in ships offers important additional advantages such as substantial reduction of greenhouse gas emissions for the need of lesser power propulsion system and a diminution of the underwater radiated noise. Last but not least important, composite materials are immune to corrosion, which improves the life cycle performance of a ship and also reduces the maintenance costs. Figure 1 shows a brief summary of the main advantages identified and expected in FIBRESHIP through using composite materials for the complete construction of vessels.

2. Project motivation

2.1. The challenge

The major challenge of the FIBRESHIP project is to enable the integral construction of large-length ships in composite materials. Nowadays, the use of composite materials in large-length structures is extensively used in the aeronautical and automotive sector. Moreover, an important number of short-length ships are built in integrally composite materials since decades ago. According to that, there is no reason to delay the complete use of composite materials in large-length ships, which will bring significant benefits for the shipping and shipbuilding industry as stated in section above.

Thus, the main purpose of FIBRESHIP is to create a new market focused on the design and construction of commercial vessels in composite materials by overcoming the technical challenges identified. In order to achieve this goal, the project is auditing new innovative FRP materials for marine applications, elaborating new guidelines for the design of composite vessels, generating production techniques for the building of large-length vessels and developing new inspection methodologies based on numerical software tools. It is worthy to note that the different technologies generated in FIBRESHIP project are experimentally validated in a real-scale structure (demonstrator) and verified by using the most advanced numerical simulation techniques.

2.2. The expected impact

The massive application of FRP materials in large-length ships, as well as the development of new construction principles for large-length composite vessels will result in a step forward in vessel efficiency. The vast experience of shipyards in the construction of small-length vessels indicates that a significant lightship weight reduction in the range of 30-40% can be accomplished by the massive employment of FRP materials. Currently, an important number of studies in the literature have confirmed this range, and even higher weight reductions [1, 2, 3]. Accordingly, the structural designs carried out in the project of the three targeted vessels confirms these studies. As a result, the fuel consumption of lightweight composite vessels is smaller in comparison with steel-based ships [4]. Furthermore, an important decrease in greenhouse gas (GHG) emissions is achieved by the reduction in the fuel consumption. This is attributed to the fact that the weight reduction directly reduces the consumption costs per ton and increases considerably the payload capacity of the vessel. On top of that, the operational costs of FRP ships are considered to be lower than conventional steel ships due to the lack of corrosion phenomenon in FRP. Finally, a reduction of the ships underwater noise signature is expected as well due to the massive application of composites in the ship structure which is caused by their features in terms of damping and stiffness.

Fig. 2 Vessels categories selected and type of vessels evaluated in FIBRESHIP

2.3. General project information and field of application

Three vessels categories have been targeted as the most promising for market orientation which are referred to as lightweight commercial vessels, passengers transportation and leisure vessels and special services vessels. In this regard, a container vessel, a ROPAX and a fishing research vessel (FRV) have been selected respectively as the most representative vessels for each category. Based on the shipping market analysis, the main particularities for each ship are clearly defined. Figure 2 illustrates the three vessels categories designed in the FIBRESHIP project.

2.4. Stakeholders: Consortium and Advisory Board group

FIBRESHIP brings together significant representative members of the European shipbuilding and shipping industry. The consortium is composed of a network of organizations with a proven record in research and technology innovation. The consortium of FIBRESHIP project consists of 18 international companies, which play a critical role in the European maritime industry. The FIBRESHIP consortium is made up of three classification societies (LLOYD´S REGISTER, BUREAU VERITAS and RINA), three medium-sized European shipbuilders (IXBLUE, NAVREP and TUCO), five prestigious scientific and technological organizations (ULIM, VTT, TWI, SOERMAR and CIMNE), four relevant European ship-owners (FOINIKAS, IEO, DANAOS and ANEK), and three companies with expertise in naval architecture and marine engineering (TSI, COMPASSIS and ATEKNEA). The FIBRESHIP consortium possesses both specialized and multi-disciplinary know-how which is necessary to meet the objectives of the project.

Furthermore, an Advisory Board was also created to advise, disseminate and follow-up the project and its consortium. This group is composed of several entities of maritime industry and composite materials sector such as regulatory bodies (IMO, EMSA), flag authorities (Spain, Panama, Denmark), shipyards (Fincantieri, Navantia, Harland and Wolff, and Gondan), industrial partners (Sika, Schottel, Teknocontrol, MJM marine, Galloo, and Sener), naval associations (Gican, SSA) or research centres/universities (University of Athens, Royal National Lifeboat Institution, Cehipar, and Fidamc) among others. Thus, the consortium undertakes the commitment of several companies as Advisory Board members of the project, which ensures the impact of this project to the European shipbuilding and engineering sector.

3. Thematic areas

A schematic description of the different work packages with thematic areas of the FIBRESHIP project is shown in Figure 3. From the figure, it can be appreciated that the project is organized as ten different work packages, which are distributed into four thematic areas: (i) "shipping market and business analysis" includes WP1 and WP8, (ii) "materials, components and modelling" considers WP2, (iii) "design and engineering" includes WP3 and WP4, and (iv) "production and life cycle management" considers WP5, WP6 and WP7. Dissemination activities are in WP9 and finally, WP10 consists of project management and coordination.

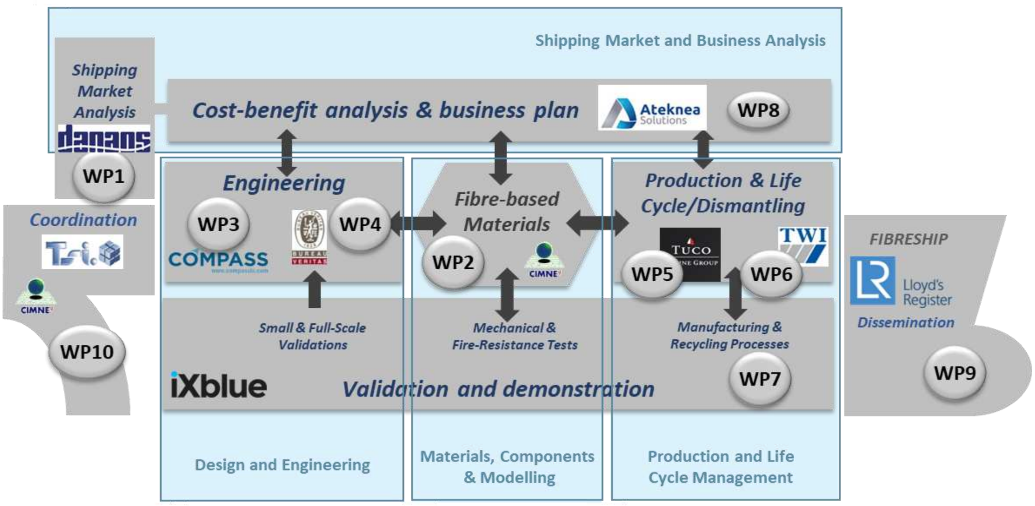

Fig. 3 Description of the thematic areas and work packages of the FIBRESHIP project

3.1. Shipping market and business analysis

Initially, a detailed analysis of the shipping market is performed with the aim to identify potential niches markets and validate the selection of vessels categories. To address this task, the current situation of the market is analysed using a SWOT (Strengths, Weaknesses, Opportunities, Threats) and 4Ps (products, place, promotion, and price) marketing analysis. The main objective of these analysis is to investigate the susceptibility of the large-length vessels market regarding FRP technology and the current regulation, as well as the identification of the main competitors and major difficulties for entering into the abovementioned market. The product differentiation advantages of using FRP materials in the construction of ships are clearly identified and quantified in the shipping market analysis. These economic studies are essential to ensure the financial feasibility and economic advantage of using composite materials in shipbuilding.

As conclusions of the shipping market analysis, the market interest on large-length FRP-based ships, the applicability area and the usability time window are defined. This is addressed by establishing the three vessels categories and detailed specifications for three ships designs. In order to ensure the industrial relevance of the project, the cost effectiveness and commercial potential of large length FRP-based vessels compared to standard steel-based ships are analysed in the project.

Furthermore, a business plan covering the different phases of the vessel life cycle (from design, shipbuilding and operation to the final dismantling of the vessel) and identifying the business opportunities for the different market players is estimated in a cost-benefit calculator developed in the project along the whole vessel life cycle. Nevertheless, changes on the regulatory frameworks with the purpose of creating guidelines and rules to promote this promising business are required, being necessary to involve regulatory bodies in this process such as IMO and flag states. On top of that, the business plan serves for the provision of economic support for making rapid decisions throughout the progress of FIBRESHIP project. This activity is an interaction between the several project stakeholders and the consortium with the aim to provide quick responses to the unforeseen expenses derived from material selection, joining techniques, maintenance, dismantling, and other day-to-day activities during the exploitation of the vessel.

Based on the market research and the cost-benefit analysis, a global business plan is elaborated and presented in the framework of FIBRESHIP at the end of the project in order to demonstrate the financial feasibility and the economic advantages of the proposed solution.

3.2. Materials, components and modelling

Conception and identification of new fibre-based materials and structural element connections for its use in large-length ships is one of the key aspects of the project. In this respect, FIBRESHIP project has researched the functional characteristics of fibre-based materials newly introduced in aerospace, automotive and wind energy systems, as well as several joining techniques used in recently completed R&D projects to assess their potential for large-length shipbuilding.

A list of potential composite materials for the construction of light-weight ships has been elaborated. With the aim to select the most appropriated composite materials, the corresponding manufacturing process and processing methods (e.g. resin infusion, compression moulding/hot press forming, automated tape placement, vacuum assisted resin transfer moulding or autoclave) have been evaluated. Furthermore, the use of recycled materials and other potential alternatives are also considered in order to evaluate lower costs options.

The selection of the composite mats used in large-length vessels is based on materials available on the market and novel fibre-based material systems. As a result, a selection methodology has been developed. Under this selection methodology, an extensive list of potential candidates has been evaluated considering different parameters of interest based on mechanical properties, fire resistance, cost, scalability, availability, and environmental performance, obtained through an extensive small-scale experimental test campaign that includes mechanical, fatigue and fire testing. From this composite materials selection methodology for large-length vessels, two materials were down-selected.

The experimental campaign was divided into three sets of experiments with the purpose to obtain a comprehensive picture of the material behaviour: (i) Mechanical characterization tests: Static testing of composite laminates with various lay-ups to determine the key mechanical properties of the specimens under different loading conditions (tension, compression and shear). (ii) Fatigue performance tests: to determine degradation of the mechanical properties (i.e. stiffness, flexural strength or strength) under cyclic loading. The loss of stiffness due to the accumulation of fatigue damage was determined via quasi-static stiffness at discrete cycle intervals. In addition, small sections of the composites were analysed through microscopic techniques with the aim to identify the failure modes of the specimens (matrix cracking, delamination, fibre-resin debonding or fibre breakage). (iii) Fire performance tests: a laboratory-scale experimental study was performed to characterize the material properties related to solid-phase pyrolysis and gas-phase combustion. The results of the fire tests provided important information on the material's thermal degradation behaviour, smoke production, toxicity and other fire behaviour of the materials.

On the other hand, a comprehensive study of the different structural elements joinings has been carried out, which are necessary for the modular process of large length ship constructions. In order to achieve this goal, it is necessary to assess the performance of the connections between the different parts of the ship structures (i.e. hull and deck) and the modular sections of the vessel. The expertise of composite connections for small-length ships has been adapted to the new requirements of FIBRESHIP, which demands solid structural connections to obtain the optimal solution for bonding cases. It is worthy to note that the selection of vessel structural joinings have been also tested.

The results obtained in these experimental tests were used to validate developed numerical models (both material constitutive model and joinings model) in the project, with special emphasis on the failure modes due to delamination, fatigue and fire.

As final finding, this thematic area has produced a catalogue of potential materials and joining techniques for building large-length composite ships, being a tool through the conception, identification, and assessment to aid in the definition of material guidelines and regulatory documents, considering fibre-based materials and consistent joining solutions for shipbuilding industry.

3.3. Design and engineering

Currently the use of composite materials is limited to small vessels (length < 50m) and secondary structural parts of the ship (e.g. superstructure). This is due to the absence of structural design rules and guidelines for building large-length composite ships. Hence, it is urgent to impulse a new regulatory framework for the integral use of FRP materials on board ships.

In the last decade, a big number of software tools have been used to simulate the steel structures of vessels and the composite structures of small ships. In contrast, there are no numerical tools to simulate the composite structures of large-length vessels. Thus, it is of paramount importance to adapt the current analysis software tools for the design and assessment of large composite vessels.

Based on the shipping market analysis, the FIBRESHIP project considered the design of three vessel concepts that are targeted as the most promising for market orientation: lightweight commercial vessels, passenger transportation and leisure vessels, and special service vessels (see Fig. 2). The methodologies, technologies and software tools developed in the FIBRESHIP project are used for the correct design of the three representative vessels and the assessment of the technical challenges resulting from the fact that they are completely built in fibre-based materials.

On the other hand, the major challenge of this thematic area is to develop project design guidelines for the design and certification of large-length composite vessels. These guidelines pretend to regulate all the required aspects related to the engineering basics, structural design and fire protection, for any vessel of the three targeted categories. To achieve this goal, the classification society's criteria is used, which is based on a main part applicable for each vessel category and specific annexes for the particularities of each one.

The methodology conceived to achieve the proposed goals, start with the design of three vessels– (corresponding to each one of the three targeted categories) and the assessment of the technical challenges resulting from the fact that they are completely built in fibre-based materials. In addition, several computational analyses are performed to assess the global structure behaviour during a fire event (collapse study). The fire scenarios are simulated using standard time-temperature curves and realistic fire descriptions.

It is well known that the underwater signature of fishing research vessels should be minimum during the fishing operation. Therefore, an underwater radiated noise analysis is performed to demonstrate the environmental impact benefits arising from the construction of fishing vessels using FRP materials.

On the other hand, the composite structures of large-length ships need to withstand cyclic loads due to the sea waves. Therefore, it is essential to develop advanced simulation tools which are able to monitor the sea waves stresses and optimize the lifetime of FRP-based ship structures. Thus, the work package six of the FIBRESHIP project is developing a structural health system to assess the structural integrity of large-length FRP ships during their life time. The computational solution based on innovative computational tools that combines existing advanced time-domain seakeeping solvers with state-of-the-art multi-scale FEA formulations to predict the mechanical response of FRP structures.

The fire behaviour of the designed vessels for various real fire scenarios is studied using a coupled CFD and FEA fire simulation tool, whose framework is developed in a previous EU project. Moreover, an existing thermo-mechanical analysis tool is proposed to investigate the temperature dependence of the elastic properties, the yield limit of the FRP materials, and the thermal degradation of the mechanical properties. The influence of the temperature on the nonlinear behaviour of the FRP material is included in the model by means of a thermal damage variable.

The advanced numerical models developed in the FIBRESHIP project are integrated in the same CAE/FEA software. The purpose of the software is to assess the different failure modes of FRP materials as for example delamination, fibre breakage, or matrix cracking. The numerical tools are under validation using standard benchmarks and the experimental results obtained in the medium and large-tests.

3.4. Production and life cycle management

The use of composite materials in the design and construction of large-length ships may result in higher building costs. Therefore, it is of vital importance to control the cost of the composite fabrication process and guarantee the economic viability of the project by using cost-efficient production technologies. The guidelines for the new production procedures should be validated by the classification societies in order to fulfil the technical requirements commonly used in the marine industry. Last, the technical feasibility and cost to adapt existing small and medium shipyards to this new market is analysed as well. In this sense, the major challenge of the FIBRESHIP project is to understand how the shipbuilding European industries should work in order to impulse a new regulatory framework, which allows the design and construction of large-length ships in composite materials.

In order to show the achievements and technological breakthroughs of the FIBRESHIP project in composite materials vessel design, a real scale demonstrator of a Fishing Research Vessel built at IXBLUE shipyard. The purpose of the demonstrator is to identify the weak points of the composite structures, validate the results from the numerical simulations, and evaluate the fabrication techniques for the composites, among others. The demonstrator is inaugurated in the 2nd FIBRESHIP Workshop which was held in Marseilles (France) at the end of June 2019.During this workshop, it was demonstrated the economic viability of the project, the lesser environmental impact on the underwater signature of vessels, and the sustainability of these technologies in the maritime industry.

Structural health monitoring of vessels is important to reduce operational costs over the ship's life cycle. Therefore, it is necessary to develop new inspection procedures, and long-term damage control strategies to evaluate in real-time the structural health of composite vessels. In this regard, one of the objectives of the FIBRESHIP project was to develop a numerical procedure to predict the health state of the vessel. This procedure is based on the use of sensors for real-time monitoring of the vessel deformations. The main idea was to monitor the global status of the vessel structure due to the effect of sea waves on the hull during navigation. As a result, the cyclic displacements between the bow and the stern of the vessel (hogging and sagging motions) were measured and monitored with the aim to control and foresee potential structure failures.

From the waste management point of view, the FIBRESHIP project carried out activities to analyse the management of waste generated during the fabrication, life cycle, and dismantling activities of the vessel.

4. Fibreship main outcomes

FIBRESHIP is an ambitious European project focused on the development of a new shipping market based on the full design of large-length commercial vessels in lightweight composite materials. The major advantages of the massive application of composite materials in the construction of ships are a greater payload cargo capacity, a diminution of greenhouse gas (GHG) emissions and a significant reduction of bunkering consumption which results in important cost-savings for the shipowners and less pollution for the environment according to the current EU policies (Directive 2012/33/EU) and the IMO target of a 50% reduction of GHG emissions by 2050. On the basis of results and findings obtained in the four different thematic areas of the project, a list of the main achievements and milestones of the FIBRESHIP project is presented.

4.1. Selection of FRP materials for the vessels

The FIBRESHIP project aims to select composite laminates with optimum mechanical and fire performance to design the lightweight vessels developed in the framework of the project. To achieve this goal, the mechanical performance of seven marine composites widely used in the naval industry are analysed. The main purpose of this investigation is to find out which class of laminates are more appropriated for the different structural elements which are involved the design of the structure of FIBRESHIP vessels.

For the analysis of material performance, a large number of mechanical tests (e.g. tensile, shear, fatigue, three-point bending and interlaminar shear strength tests) are carried out to characterize the material behaviour of the laminates under various types of stresses. The findings obtained in this experimental campaign showed that the seven tested materials for the vessel construction possess acceptable mechanical performance to withstand the most severe static and dynamic loads. A recent study of FIBRESHIP regarding this experimental campaign has been reported in [5], this publication deals with the identification of suitable commercially available resin systems for the manufacture of composite structures in marine vessels greater than 50 m-length. Thus, this study summarizes part of the selection procedure utilized to identify the most suitable materials for the building of the new large length vessels developed in FIBRESHIP.

For the investigation of fire behaviour, a small-scale fire testing campaign is performed at VTT premises to study the fire performance of the selected composite material systems. To evaluate the fire performance of the laminates, the time to ignition, heat release and smoke production of the composite laminates are determined using a cone calorimeter. The results of this tests kindly provided by Technical Research Centre of Finland (VTT) [6] can be seen in Table 1. The table shows the time to ignition (tig), the maximum heat release rate (HRRmax), the total heat release (THR) and the total smoke production (TSP) for the seven composite materials tested in this experimental campaign. The experimental data shown in the table revealed that the specimens based on phenolic resin system (Cellobond J2027) showed the best fire performance in terms of both time to ignition, heat release as well as smoke production. In contrast, the specimens manufactured with Elium polymeric resin show the shortest time to ignition, intermediate values of heat release and low smoke production. The specimens based on epoxy resin (Prime 27, SR 1125, Super Sap CLR) showed similar behaviour in terms of times to ignition. However, the heat release and smoke production of the specimens are considerable high. The laminates based on LEO system with an intumescent topcoat show a long ignition time (75 s) and low values of smoke production (8.8 m2) or heat release rate (69 kW/m2) which indicates a good-reaction-to-fire performance. A very detailed analysis about the fire and thermal behaviour of the seven composite laminates selected for the construction of the FIBRESHIPs can be found on deliverable D2.4 of the FIBRESHIP project [6].

In general, it is noticed that the LEO resin system based on vinylester provided acceptable mechanical properties and superior fire performance. Due to their excellent mechanical and fire behaviour, the Leo System with topcoat is selected as a potential resin for the manufacturing of the laminates used in the new vessel designs. Eventually, it is also important to mention that FIBRESHIP performed real-case fire simulations to assess the fire propagation in different fire scenarios. In this regard, it should be pointed out that the nature of the composite materials and the fire location play a critical role in fire propagation.

Specimen	t_{ig} (s)	HRR_{max} (kW/m^2)	THR (MJ/m^2)	TSP (m^2)
LEO system with topcoat	75	69	42.3	8.8
Crestapol 1210	44	314	35.4	9.3
Prime 27	60	496	39.4	10.7
SR1125 with SGi 128 topcoat	52	261	40.7	9.3
Super Sap CLR	61	520	42.0	12.0
Cellobond J2027X	101	71	9.9	0.4
Elium	23	255	40.7	1.8

Table 1 - Results of the Cone calorimeter test for seven composite laminates

4.2. Design and Construction of a ship block of a Fishing Research Vessel as a demonstrator

A real-scale module of the Fishing Research Vessel (FRV) with a length of 11 m, a width of 11 m and a height of 8.6 meters has been constructed at iXblue shipyard to demonstrate the technological achievements and breakthroughs of FIBRESHIP project. A photography of the FRV demonstrator constructed integrally in composite materials is depicted in Figure 4. The demonstrator has been designed by the Spanish company Técnicas y Servicios de Ingeniería (TSI) following the recommendations of the classification societies in terms of composite material design, and fulfilling the structural criteria defined by them. This demonstrator of 20 tones results in a mix of two different parts of the vessel, considering a part of a machinery room in the bottom deck and a set of accommodation spaces in the upper deck. Figure 5 displays a three-dimensional representation of the FRV, the inset of the figure show location of the fishing research vessel demonstrator built in iXblue shipyards.

Fig. 4 Digital photography of the real-scale module of the fishing research vessel constructed at iXblue shipyards.

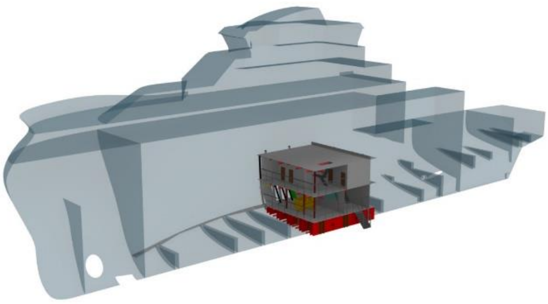

Fig. 5 Three-dimensional representation of the demonstrator location in the fishing research vessel.

4.3. Guidance notes and recommendations prepared by Classification Societies

The specific objective of this task is to prepare a catalogue of materials with the recommendations of the classification societies for the use of composite laminates and joining connections in the design and construction of large-length ships. The main purpose of the materials catalogue is to provide guidance for the users of the catalogue regarding the most appropriated composite laminates and joining connections for the large-scale ships. Special attention is paid in the catalogue about the mechanical and fire performance of the resins and fibres used for the lamination of the composites. In summary, the catalogue prepared by the Classification Societies will define the different composite laminates and joining connections that could be used in the ship construction of the FIBRESHIP vessels.

4.4. Structural health monitoring (SHM) strategy for vessels

Additionally, an experimental campaign to monitor the 260 m length hull structure of the ZIM LUANDA containership was performed in the FIBRESHIP project. This study resulted in two main achievements: (i) a set of data has been recorded to validate a hydro-structural numerical tool develop within the scope of the project; and, (ii) a SHM strategy has been defined to monitor in real-time the structural behaviour of the vessel according to the course and sea state in order to feed a twin digital model.

The main idea consists in measuring the local and global deformations of the vessel during a navigation route from Valencia (Spain) to Halifax (Canada). To carry out this test, the global deformations of the hull was measured using an array of five inclinometers and the local deformation through four sets of strain gauges located close to structural hotspots. On top of that, the real-time environmental conditions and sea state (wind speed, wind directions, wave height, wave period, wave direction, etc.) were also measured and trigged using an environmental tracker device including a GPS and an inertia measurement unit able to register the ship motions.

Some preliminary results of the structural health monitoring test carried out in the 260m-LOA containership are represented in Figure 6. The shown curves represent the rotations measured along the length of the ship using the five inclinometers for two different operational conditions during the navigation route. From this figure, it can be noticed that for operational condition 7 (significant wave height of 2.2 m and 8 s of peak period) and a forward quartering sea heading (+30deg with respect to the head sea), the rotations acquired with the inclinometers were up to 2 degrees as it is appreciated in the curves shown in Figure 6 . In contrast, more extreme metocean conditions associated to a higher wave height of 7.5 m and 12 s peak period, as well as a heading course close to a head sea (-5deg with respect to the head sea), produced an increase of rotations of up to 8 degrees (Figure 6), mainly due to the hogging and sagging motion generated by means of the wave length associated to the peak period of the wave. As a result, it can be noticed that the inclinations of the hull structure are strongly dependent on the combination of the sea state and heading during navigation due to the appearance of hogging and sagging motions. Therefore, it can be mentioned that the monitoring system successfully registered the deformation state of the containership through the navigation route between Spain and Canada, being possible to obtain the stress values reached. A more detailed description of the results obtained in the SHM strategy used for ZIM LUANDA containership has been considered for an upcoming scientific journal publication.

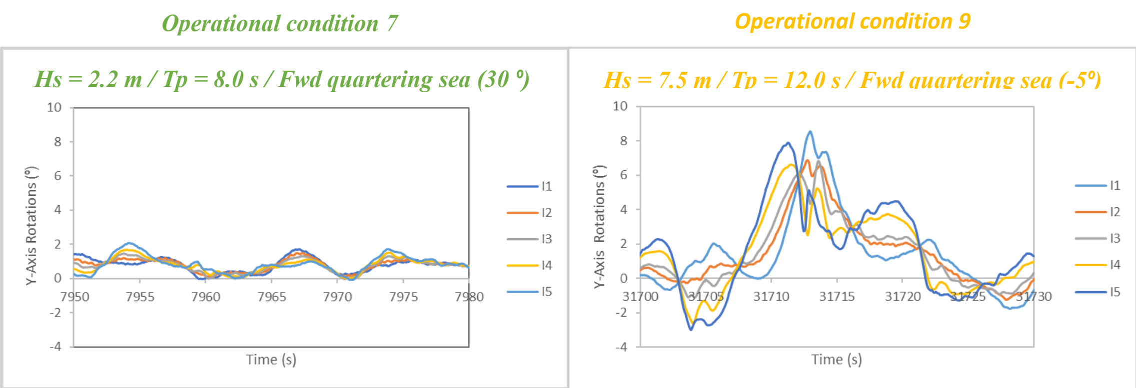

Fig. 6. Containership hull girder rotations measured by the inclinometers along the length of the ship for two different operational conditions.

4.5. Bonding connections of vessel structures

The strength of the structural connections of the FRP vessels designed in FIBRESHIP has been widely studied in the project. The fundamental idea is to analyse and optimize as possible the bonding techniques among the different structural parts and modules of the vessel. To this end, a set of experimental tests have been carried out as well as the development of a numerical model, trying to reproduce the behaviour of connections under different load needs.

Thus, an experimental campaign to assess the strength of the FIBRESHIP composites joinings has been performed. Through these data gathering, it is possible to analyse the behaviour of different bonding solutions and validate the developed numerical model. For this aim, structural connection tests are conducted at two different levels. In the first stage, coupon levels are tested to evaluate the Single Lap Shear (SLS) strength of the composite connections as well as other mechanical parameters. In the second stage, a detailed experimental campaign based on mid-scale tests was carried out to evaluate the strength of the real composite connections used in the demonstrator of the project and the ones potentially used in FIBRESHIP vessels. The results of this study are essential to set the vessel building strategy of the FRP vessels in the shipyards.

4.6. Study of the state of the art of waste management in fibre-based vessels

It is well known that a large amount of industrial waste is generated during the construction and dismantling procedures of ships. Some examples of common chemicals and hazardous wastes generated are waste water, solid wastes, hazardous materials and liquid wastes. With the purpose to minimize the amount of waste and environmental impact due to this shipping activity, it has been performed a study to analyse the current situation of the waste management, to foresee the best option to be addressed in the new future FIBRESHIP vessels.

This study analyses the current regulations and sustainable development strategies used to control and minimize the amount of waste produced by the shipping industry. On one side, the Hong Kong convention offers waste prevention measures to minimize adverse effects on human health and environment. To date, this regulation has been applied by only seven states (Turkey, Congo, Belgium, Denmark, France, Norway and Panama) which represent the 0.62% of the annual recycling volume. On the other side, the European Union has developed an alternative regulation known as the EU 1257 with the purpose of applying the regulatory framework of the Hong Kong convention in Europe. The major technical challenge of the convention is to achieve the recycling of the 3% of waste generated during the dismantling process. To achieve this goal, the European Union aims to apply this environmental regulation in all shipping disassembly centres in the near future.

The wastes generated due to the shipping activity are normally incinerated (e.g. burnt with the possibility of recovering energy), landfilled in controlled areas and recycled depending on the cost. Pyrolysis process seems to be the best option for the management of the shipping waste due to the fact that it is more environmentally friendly than others and it has a high added value due to the generation of energy in the process and the recycling of the fibres. The incineration is widely used for the elimination of shipping waste but it generates pollution emissions of dust, metals and dioxins which must be controlled using a smoke treatment system. In conclusion, FIBRESHIP is conducting an environmental study to analyse the current framework of the generated waste and how it can be focused on composites and FIBRESHIP solution in order to reduce the environmental impact of this activity in the future of the shipbuilding and shipping industry.

5. Conclusions

FIBRESHIP (H2020, Grant 723360) is an innovative research and development project aimed at developing a new market based on the design and construction of commercial ships in lightweight composites (FRP, Fibre-Reinforced Polymers) greater than 50m in length. The major challenge of this project is to create new rules and regulations for the design and construction of large-length ships in FRP materials overcoming the technical challenges identified. For this purpose, the project is qualifying and auditing new FRP materials for marine applications, elaborating new designs and production guidelines, generating production and inspection methodologies, and developing numerical tools to assess the structural performance of the new lightweight vessels.

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